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A wetland ecosystem service assessment tool; Development and application in a tropical peatland in Uganda

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ABSTRACT

We present the methodological development of a surveying and accounting tool created in response to a lack of appropriate data for modelling ecosystem services in tropical wetlands in East Africa. The survey provides a practical field methodology for quickly characterising the environmental, vegetation, soil and hydrological properties of a wetland using a nested sample site and sub-plot procedure. The accounting procedure provides simple calculations for combing these survey data with literature values to estimate ecosystem services provided by the wetland. The wetland ecosystem service assessment is based on per unit area estimates by land cover type, and scaled by areal extent of each land cover. The tool was tested and deployed in 60 locations within the Kashambya wetland complex, southwest Uganda. Results of the survey and accounting procedure are presented along with data on wetland soil, vegetation and hydrological properties. Our results, showing standard errors, demonstrate that while the Kashambya wetland has been extensively modified by anthropogenic influences, it remains a large store of water ($7.0 \pm 1.3\,m^3$) and carbon ($0.5 \pm 0.04\,M\,t$). The wetland is a large source of water vapour ($40 \pm 180\,k\,m^3\,y^{-1}$) and sink for carbon ($3 \pm 4\,k\,t\,y^{-1}$). The high uncertainty of flux estimates demonstrate the need for further biophysical modelling based upon the data captured by the survey tool. The wetland provides food production services valued as US\$ $1 \pm 0.1\,M\,y^{-1}$. Our results show that ecosystem services provided by wetlands change significantly under different land cover, but high heterogeneity of ecosystem service provision exists within land cover classes. Greater understanding of spatial dynamics is required to improve accuracy of wetland ecosystem service assessments, and to examine the implications of land management and climate change on wetland ecosystem services.

1. Introduction

Wetlands are one of the world's most important environmental assets, providing significant economic, social and cultural goods and services, including fibre, food, recreational opportunities, tourist activities, water purification, biodiversity habitat, carbon (C) sequestration, and reducing flood damage (Barbier et al., 1997; IWMI, 2014; Mitsch et al., 2015, 2013; Namaalwa et al., 2013; Russi et al., 2013). However, many wetlands across the world have undergone significant modification and land use change, resulting in impacts to ecological functions and ecosystem services (ES) (Davidson, 2014; Holden et al., 2004; Lehner and Döll, 2004; Rivers-Moore and Cowden, 2012; Schuyt, 2005).

Forecasting and modelling is required to understand the impact of land management or future climate change on wetland ES (Langan et al., 2018). There remains a lack of information on the properties of tropical wetlands to quantify ES, monitor wetland health, and assess the impact of degrading activities on wetland benefits to inform management decisions (Maltby and Acreman, 2011; Langan et al., 2018). Where data are available, values are often based on localised ranking and scoring systems that are unsuitable for assessing wetland ES due to a lack of spatial identification of wetland properties (e.g. Henninger and Landsberg, 2009). Little attention has been given to generating quality data in a simple and inexpensive way, and using data available for further applications, particularly as inputs for modelling where limited available data present challenges for using models to understand wetland ES dynamics. Concerns over the accuracy and uncertainty of model-based outputs will hinder their use in decision-making, limit our understanding of wetland ES dynamics and subsequently hamper improved management of wetland ES. High quality, basic spatial data on

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the hydrological, soil and vegetation properties of wetland ecosystems are required to support evidence-based tropical wetland ES management (Langan et al., 2018). Combining standardised wetland resource assessments with remote sensing and spatial datasets to create digital maps of wetland properties could derive much needed evidence to improve assessments of wetland ES. Limited data on wetland properties and assessment of wetland ES not sensitive to important wetland properties presents further challenges to monitoring changes to understand wetland ES dynamics over time.

The objective of the work presented here is to describe the development of a wetland ES assessment tool, and its case study application in Uganda. The wetland ES tool includes a field survey methodology for measuring wetland properties under different land covers, and a simple accounting procedure for estimating wetland functions and ES that is sensitive to underlying wetland properties. The survey methodology captures data on localised, spatially located wetland conditions suitable for modelling wetland ES, identifying soil, water and vegetation properties in geo-located sites. Field data is combined with literature values to estimate wetland functions and ES using a simple accounting procedure to estimate food, water and climate related ES. The wetland ES assessment tool is applied in Kashambya wetland complex in southwest Uganda. Collected survey data is used to estimate the current provision of ES by Kashambya wetland due to current wetland land uses and establishes a baseline for monitoring changes in ecosystem properties, ES and wetland health.

2. Materials and methods

2.1. Survey design and sampling plan

Development of the wetland ES assessment survey drew on a number of existing ecological survey methods, tools and techniques, notably the *Land Degradation Surveillance Framework* (Vågen et al., 2013), *WET Eco services* (Kotze et al., 2008), *National Soil Inventory of Scotland* (Lilly et al., 2010), *Ugandan National Wetland Inventory system* (NWIS) (Henninger and Landsberg, 2009) and *Toolkit for Ecosystem Service Site-based Assessment* (TESSA) (Peh et al., 2013). The wetland ES assessment survey was designed to collect data to understand anthropogenic influences on ecosystem functions and structure. The survey identifies general ecosystem characteristics of the sample site, and specific soil, vegetation and hydro-geomorphological properties in sample plots at sub-site level. Within the wetland system of study, a 30 m square grid covering the entire wetland was used to create 900 m^2 sampling sites that were further stratified by land cover. A random, stratified sampling strategy was used with a minimum number of four sampling sites for each strata to ensure a balance of land cover types (Olsen, 2010). Within each sample site, general wetland characteristics were assessed for the 900 m^2 site. Three sample sub-plots were randomly created using vegetation quadrats to identify key vegetation properties. An assessment of the soil was made using a peat auger to identify key soil characteristics down the soil profile, and soil samples were taken. A qualitative assessment of site hydrological characteristics was made, and a water sample was taken where surface water was present. Where wetland soil was exposed, an infiltration ring was used to determine the infiltration rates. The survey was administered using an android smart phone and the freely available Open Data Kit application[1] (Open Data Kit Core Development Team, 2014), with additional note-sheets to support fieldwork data recording not suited to smartphones, e.g. soil profile descriptions (Annex B).

[1] Open Data Kit xml data file is available on request. A paper version of the survey is provided in Annex A.

2.2. Site sampling protocol

The wetland ES assessment captured information to characterise the site sampling location and made an assessment of the full 30 × 30 m sample site. Data recorded at the site level contained general site information including location and photographs, landform, land cover characterisation, land use and management, and anthropogenic influences on the wetland. The landform assessment identified the broad land cover class, slope, position within the catchment (upper or lower) and the wetland (edge or centre), and hydro-geomorphological classification. Land cover classification was based on a modified version of the Uganda National Wetland Inventory System (Henninger and Landsberg, 2009) comprising of 11 wetland land cover categories including swamp forest, woodland, shrubland, bushland and palms, papyrus, reeds, open water, natural grassland, grazing, cultivated and plantation forestry. Wetland hydro-geomorphological classification was based on definitions given by Kotze et al. (2008) and described the key topographical situation of the sample site as flood plain, valley bottom with/without channel, lake fringe, isolated seepage, floating, raised bog, hill-slope or depression. An assessment of sample site water regime and seasonal coefficient was made by assessing the number of months that the water table was within 10 cm of the soil surface as permanent (> 8 months), seasonal (> 2 months < 8 months), temporary (< 2 months) or dry (freely draining) (Table 1). Land cover was assessed for the sample site by identifying the vegetation type and species, and their coverage of the sample site, as assessed using the "Braun-Blanquet" vegetation rating scale (Braun-Blanquet, 1928 as described in Moore, 1962) from 0 (bare) to 5 (> 65% coverage). Surface water and bare soil exposure assessments were also carried out using the Braun-Blanquet scale. Information on the land use, management and ownership type of the sample site was assessed. The assessment identified any direct uses of the wetland such as food cultivation, timber, fuel wood, forage, grazing, brickmaking, sand mining, water collection or fishing. The ownership of the land was recorded, as perceived by local wetland users. Observations on human influences on wetland structure within the site were made to examine and record the evidence of anthropogenic impacts and management practices, in or adjacent to the site, including the presence of tree planting, grazing, crop cultivation, vegetation harvesting, fire, soil drainage or disturbance. The evidence for each anthropogenic influence was described and the impact assessed on a four-point scale from *none* to *high*. Detailed definitions for all classifications are provided in Annex A.

2.3. Plot sampling protocol

Plot level sampling provided a fine scale assessment of important ecosystem properties, divided into vegetation, water and soil assessments. Tree, shrub and herbaceous vegetation properties were assessed using randomly placed quadrat within the representative vegetation types within the site sample. Note that vegetation type may need to be differentiated further into sub classes, for example in the case of heavy grazing or if browsing pressures are present. A water assessment identified key hydrological properties including water sources and water table depth. A soil assessment was made in one of the randomly located quadrats, developing a soil profile description, taking soil sample for laboratory analysis and qualitative description of site soil properties.

2.3.1. Vegetation survey assessment

The vegetation survey assessment estimated standing biomass, above ground biomass C storage, and the impact of harvesting, grazing and fire on vegetation within the plot. For trees and shrubs, one 3 × 3 m quadrat was used, while three 1 × 1 m quadrats were used for herbaceous vegetation. Recorded vegetation properties included vegetation species and type, condition, age class (juvenile, established, mature, senescent), stand height, canopy cover and disturbance. For

Table 1
Definitions of wetland hydrology and seasonal coefficients (*Cs*).

Wetland hydrology	Definition	*Cs*
Permanent	Soil is inundated for over 8 months of the year	1
Seasonal	Surface water present up to 8 months of the year, except in the height of the dry season	0.667
Temporary	Surface water present only during the 2 months of the wet season	0.167
Dry	Wetland is no longer wet for prolonged periods of time	0

trees and shrubs, stem diameter was recorded by measuring the circumference of the stem at a height of 130 cm for trees or 5 cm for shrubs, along with the height of individual trees. For herbaceous vegetation, stem density was recorded before harvesting and weighing herbaceous biomass within each quadrat. Plant samples were taken by selecting three average size plants, one small and one large plant, and placing them in labelled and sealed plastic bags for laboratory analysis of dry weight. The dry weight of the five plants sample was used to estimate water – biomass ratios for vegetation.

2.3.2. Water survey assessment

Evidence of hydrological properties of the wetland within the sample site were assessed using a modified version of the methodology provided by Kotze et al. (2008) for classifying drainage density, hydrological connectivity, flooding likelihood and flow resistance based upon a 4-point scale from *zero* to *high* (see Annex A for descriptions). Drainage density was assessed as *zero* where no field drains were observed, *low* where distance between field drained was > 15 m, *moderate* where field drain spacing was between 15 and 3 m and *high* where field drains were closer than 3 m apart. The hydrological connectivity of plots was assessed based on proximity and height to central drainage channels and stream network, and the presence of barriers preventing water flowing into the site. Evidence of flood damage and deposits was assessed qualitatively based on field observations to determine *Zero, Low, Moderate or High* evidence of flooding. Plot resistance to flooding was assessed based on vegetation structure and the presence of microtopographical soil structures (see Annex A for descriptions). Field drain and water table depths were measured. If surface water was present within 10 cm of the surface, a 50 dm^3 sample of water was taken in a clear glass vial, photographed with a colour correction card and described on a separate note sheet (Annex B). Water samples were analysed using a number of visual assessments and measurement tests. Water samples were first left to settle, then measurements of the volume of sediment deposits were made, and colour and texture assessment of suspended and deposited sediment were recorded. Samples were then shaken for 30 s, and colour and texture assessments were again made for the sample. A water quality classification was made based upon the amount of suspended sediment.

2.3.3. Soil survey assessment

A soil survey assessment was used to characterise and describe the wetland soil properties. A peat auger was used to collect peat samples at 50 cm intervals in the top 2 m of soil. Soil profile layers were identified, photographed and described based on soil material composition, level of organic matter decomposition, mineral soil content, colour, soil textural descriptions, field observations of soil moisture and bulk density, and sub-soil material composition. A sample of each soil profile layer was individually bagged for laboratory analysis. Profile descriptions were summarised using a logical hierarchical decision-tree to determine soil type by categorising soil profiles into for four, broad peat soil classes: Drained peats, Seasonally wet peats, Saturated peats, and Lake deposit peats (Annex C). Peat depths were recorded by further checking 50 cm increments down the profile until the underlying grey clay below the peat layer was reached. Any observations of soil erosion and fluvial deposition and impacts of land management were recorded along with its location within the soil profile; typically the presence of a mineral soil layer either on the soil surface or at a particular depth (Farmer et al., 2016).

Laboratory analysis of soil samples included fresh weight, dry weight, bulk density, pH, macronutrient analysis and organic matter content using techniques specifically developed for organic soils in Uganda (Farmer et al., 2016). Organic matter content was measured using loss on ignition, and soil carbon was calculated using an organic matter carbon fraction of 53% (Farmer et al., 2016). Soil results were compiled into three depth layers for further analysis; top layer (top soil layer of the profile, regardless of depth), surface layers (all soil layers within 50 cm of the soil surface), and sub surface (all soil layers between 50 and 100 cm). Carbon density was then calculated using a weighted mean for each soil layer to allow comparison between sample points.

At sites where the soil surface was > 10 cm above the water table depth, the infiltration capacity of the soil was measured using a single ring infiltrometer. Vegetation was removed from inside the ring, taking care not to disturb the soil surface or roots. Approximately 2 dm^3 of water was used to dampen the soil 5 min prior to commencing the experiment. The infiltrometer was filled to a height of 20 cm above the soil level and measured and refilled over 5 min intervals. Measurements ceased after at least 30 min had passed and water level changes had remained stable over a 15 min period. Infiltration rates were estimated by taking the mean of the final three instantaneous infiltration rate measurements (Crockett et al., 2016).

2.4. Accounting wetland ecosystems services

2.4.1. Model description, setup and assumptions

A simple model was developed to quantify wetland ES. Nine key ecological functions were identified as providing important benefits from wetlands within three broad categories of water provisioning and regulation (water availability, water balance, water quality, water purification and flood storage), climate regulation (total C stock and C fluxes) and food production (crop yield and milk production).

Estimates of ES on an areal basis were developed for each sample site by combining field measurements, described above, and regionally appropriate default values from literature. Mean and standard error of ES provision for each wetland land cover was calculated. Land cover data was used to scale unit area estimates of wetland ES by land cover area to estimate total wetland ES provision and standard error.

2.4.2. Water availability

Water availability is defined here as the stock of water available to use for household, agricultural (livestock and irrigation) and industrial uses. For wetlands in south western Uganda, water availability is dominated by surface water as underlying clay horizons prevent interactions with groundwater. Surface water availability was calculated based upon field measurement of water table depths and an assessment of seasonality of the water regime as permanent, seasonal, temporary or dry (see Table 1). Annual water availability (WA_A) ($m^3\,ha^{-1}$) is given by the equation;

$$WA_A = WTD \times Cs \times 100 \tag{1}$$

where *WTD* is the measured water table depth (cm) (multiplication by 100 converts from cm to $m^3\,ha^{-1}$), and *Cs* is the seasonal coefficient describing the proportion of the year where surface water is available (Table 1).

2.4.3. Water balance

The water balance is an estimate of the water fluxes occurring within a wetland due to surplus incoming water from precipitation over losses due to evapotranspiration and water extractions. This simple model does not capture the role of surface flow dynamics, but instead

assumes that these are approximately in equilibrium, i.e. what flows from upstream and infiltration is approximately equal to outflow and runoff. Annual water balance (WB_A) ($m^3 ha^{-1} y^{-1}$) is given by the equation;

$$WB_A = (MAP - (Et_o \times K_i)) \times 10 - Ex \quad (2)$$

where MAP is the mean annual precipitation ($mm\,y^{-1}$), Et_o is mean annual reference point evapotranspiration ($mm\,y^{-1}$) (multiplication by 10 converts from $mm\,y^{-1}$ to $m^3 ha^{-1} y^{-1}$), K_i is evapotranspiration coefficient for the tropical land cover class, *i*, based on literature values and Ex ($m^3 ha^{-1} y^{-1}$) is the field-based assessment of any water extractions from the wetland. The Penman-Monteith equation was used to calculate reference point evapotranspiration (Allen et al., 1998). Land cover evapotranspiration coefficients were estimated using FAO default values for tropical regions, and literature values for regional papyrus rates (Allen et al., 1998; Saunders et al., 2013). The evapotranspiration coefficient for papyrus land cover, $K_{papyrus}$, was estimated as 0.8 ± 0.3 based on evapotranspiration data of papyrus vegetation in three East Africa studies Jones and Muthuri, 1997; Rijks, 1969; Saunders et al., 2007). Due to the thick canopy cover of papyrus, it can be assumed that this is the dominant component of evapotranspiration in this land cover.

2.4.4. Water quality and purification

Field observations of visible sediment loading in water samples were reclassified as good or poor water quality based upon *low* or *moderate* to *high* visible sediment loading. In the absence of temporal, quantitative data on the capacity wetlands to purify and filter water, an indicator framework identifying wetland properties and land management practices that are likely to contribute to changes in visual water quality was used. Natural wetland vegetation and surface water were assumed to contribute to improved visual water quality by slowing water flows, resulting in deposition of suspended sediments (Langan et al., 2018; Naiman and Henri, 1997). Negative impacts on water quality include run off and leaching associated with soil exposure and disturbance (Acreman et al., 2007; Bullock and Acreman, 2003; Kaggwa et al., 2010, 2001; Kansiime et al., 2007; Kanyiginya et al., 2010; Mugisha et al., 2007). The likelihood of a site contributing to water purification services was assessed by combining indicators for wetland properties contributing to water purification surfaces, i.e. wetland vegetation and surface water, and properties contributing to poor water quality i.e. exposed bare soil and soil disturbance. A water purification score ($SC_{water\ purification}$) was obtained for each site on a scale of −10–10, where a highly negative score signifies a negative contribution to visual water quality and vice-versa. This is given by the equation:

$$SC_{waterpurification} = (C_{surfacewater} \times (f_{veg} + 1)) - (C_{baresoil} \times (f_{soil} + 1)) \quad (3)$$

where $C_{surface\ water}$ is the field assessment of surface water area (Braun-Blanquet scale), f_{veg} accounts for the presence of wetland vegetation to purify water (*yes(1), no(0)*), $C_{bare\ soil}$ is field assessment of bare soil exposure (Braun-Blanquet scale), and f_{soil} accounts for the presence of soil management practices disturbing soil structure and contributing to poor water quality (*yes(1), no(0)*). Water purification assessment was made by classifying water purification score into four classes; *Strongly positive* ($SC_{water\ purification} > 5$), *Weakly positive* ($SC_{water\ purification} > 0$), *Weakly negative* ($SC_{water\ purification} > -5$) *and Strongly negative* ($SC_{water\ purification} < -5$).

2.4.5. Flood storage

Due to limited flood extent and river discharge data in the region, an indicator model was developed to identify the likely ability of the wetland site to store floodwater. The ability for wetlands to store floodwaters depends upon the capability of a wetland to store water, connectivity to flood water flows and its potential capacity to store water. Floodwater storage occurs within the soil in non-saturated wetland soils although this tends to play a minor role compared to above surface storage in the presence of restrictions on surface water flows and topography (Acreman and Holden, 2013; Acreman et al., 2011; Bullock and Acreman, 2003). Assessments of hydrological connectivity accounted for distance, height and presence of barriers to central water flows through the wetland, and the capacity of a wetland to store floodwater was based on land cover resistance to flood water due to micro-topography and vegetative structure (Acreman and Holden, 2013; Harvey et al., 2009; Kotze et al., 2008). A floodwater storage assessment was based upon combining hydro-geomorphological indicators to create a flood storage score ($SC_{flood\ storage}$) given by the equation;

$$SC_{floodstorage} = (SC_{waterstorage} + 1) \times SC_{connectivity} \times SC_{floodresistance} \quad (4)$$

where $SC_{water\ storage}$ is the field assessment of the wetlands capability to store water based upon the presence of surface water (*yes(1), no(0)*), $SC_{connectivity}$ is the field assessment of hydrological connectivity of site to flood water flows on a scale of *zero*(1) to *high*(4), and $SC_{flood\ resistance}$ is the field assessment of resistance of the wetland to floodwater flows on a scale of *zero*(1) to *high*(4). A flood storage assessment was made by classifying flood storage score into three categories; *high* ($SC_{flood\ storage} > 20$), *moderate* ($20 > SC_{flood\ storage} > 10$) and *low* ($10 > SC_{flood\ storage}$). Definitions for the classification of $SC_{connectivity}$ and $SC_{flood\ resistance}$ scores are detailed within the survey form in Annex A.

2.4.6. Total ecosystem carbon

Total ecosystem C stock was estimated for each land use type as the sum of soil and vegetation C pools. Above ground biomass calculations are based upon field measurements for tree, papyrus, reed and cultivated plant types. Grass and weed biomass measurements are based upon field measurements of vegetation coverage and a default C density of $1.265\,kg\,m^{-2}$ for East African grassland (Deshmukh, 1986). Soil C stocks were estimated by field measurements of C density and peat depth. Total ecosystem C (TEC) ($t\,ha^{-1}$) is given by the equation;

$$TEC = \sum_i (AGB_i \times Cveg_i) + (P_{depth} \times \rho c \times 100)) \quad (5)$$

where AGB_i is measured above ground biomass C stock for vegetation type *i* (tree, papyrus, reed or cropland) or literature values for grass and weeds ($t\,ha^{-1}$), $Cveg_i$ is the proportional coverage of the sample site by vegetation type i based upon Braun-Blanquet scale assessment score, P_{depth} (cm) is the measured peat soil depth and ρc is measured soil C density ($g\,cm^{-3}$).

2.4.7. Carbon flux

Carbon fluxes were estimated from three major pathways; fixation of C into the ecosystem due to net primary production (NPP) from photosynthesis of vegetation, emissions of C due to decomposition of soil organic matter (SOM) following wetland drainage, and removal of C through harvesting and removal of vegetation. Rates of NPP for the dominant vegetation type, C_{NPP} ($t\,ha^{-1} y^{-1}$), were based upon default values for external data sources. Papyrus and crop NPP rates were based upon localised field data (ALTER, 2016; Farmer et al. *In prep*). Regional default values for annual NPP were used for reeds and grass (Deshmukh, 1986). Forest NPP was based on regional default values for Eucalyptus plantations in Uganda, assuming mean NPP over the 20 year life span of the plantation (Alder et al., 2003). Carbon emissions from SOM decomposition in submerged soil conditions were assumed to be zero. Carbon emissions due to SOM decomposition following tillage and drainage of highly organic soils, C_{decomp} ($t\,ha^{-1} y^{-1}$), were estimated from field measurements in Kabale to be $17 \pm 7\,t\,ha^{-1} y^{-1}$ and $13 \pm 5\,t\,ha^{-1} y^{-1}$ respectively (Famer et al. *In prep*). Eucalyptus forestry on organic soils induces further drying, estimated to increase C emissions from soils under each tree by $4.0\,g\,hr^{-1}$ (Wardle et al., 2015); this was scaled up to give annual C fluxes from each tree of $0.033\,t\,y^{-1}$. The annual C flux, $CFlux$ ($t\,ha^{-1}$), was then given by the equation

$$CFlux = C_{NPP} - (C_{decomp} \times (1 - Cs)) - (\rho_{tree} \times 0.033) - VR \quad (6)$$

where Cs is the seasonal coefficient giving the proportion of the year where soil surface is submerged, ρ_{tree} is the measured density of eucalyptus trees (ha^{-1}), and VR is the measured removals of C by harvesting ($t\,y^{-1}$).

2.4.8. Food production

Assessment of food production ES includes the market value of potato and milk production from wetland areas. Potato yields were the only crop considered, as this is the primary agricultural activity in the region. However, it is worth noting that some farmers also grow cabbages outside the main wetland cultivating season. Field measurements of potato yields show the mean wetland crop yield in Kabale wetlands is 14 (± 0.9) $t\,ha^{-1}$ (Famer et al. *In prep*). Not all potatoes grown can be sold due to small size and field measurements suggested that 37 (± 2)% of the potato crop by weight was too small for sale, and was used for household consumption. In 2015, a 125 kg sack of potatoes sold for 80,000 UGX (ALTER, 2015), equivalent to 559 US$ t^{-1} using purchasing power parity factor[2] (ppp). Therefore, the value of annual potato production (Val_{potato}) (US$ $ha^{-1}\,y^{1}$) in the cultivated land cover type was given by

$$Val_{potato} = 14 \times 63\% \times 559 \quad (7)$$

Milk production was estimated from literature values of regional data of herd densities and milk yields (Hemme and Otte, 2010; Ndambi and Hemme, 2009; Balikowa, 2011; Nakiganda and Ahmed, 2014; UBOS and MAAIF, 2009). Wetland grazing was assumed for a medium size extensive dairy farming system as described in Hemme and Otte (2010) as this is the most common livestock farming system in the wetlands of the south western region of Uganda. This livestock system holds a grazing stocking density of 1.9 cows ha^{-1} (Hemme and Otte, 2010). Regional statistics show that mean milk production per cow is 505 $dm^3\,y^{-1}$ (Ndambi and Hemme, 2009). This was used to estimate the annual value of milk production based on a farm gate price for milk of 400 UGX dm^{-3}, equivalent to US$ 0.35[2] ppp (Balikowa, 2011; Nakiganda and Ahmed, 2014; UBOS and MAAIF, 2009). Annual milk production (Val_{milk}) (US$ ha^{-1}) for grass and reed land cover where grazing was identified was given by the equation;

$$Val_{milk} = 952 \times (1 - Cs) \times 0.35 \quad (8)$$

where Cs is the seasonal coefficient given by the proportion of the year where surface water is present and grazing not possible.

3. Case study – Kashambya wetland complex in Kabale, Uganda

The wetland ES assessment survey tool was developed during field trials in wetland sites in Kabale District, Uganda. Wetland systems in Kabale are characterised by valley bottom, fluvial fed wetlands under a gradient of wetland land use change, including intact papyrus and wetland potato cultivation. The wetland ES methodology was used to characterise 59 sample sites in November 2016. This field data was combined with accounting procedure and land cover data to estimate the total and standard error of ES provided by the wetland complex. Land cover data was created by semi-manual classification of European Space Agency's Sentinel-2 satellite remote sensing data and cross-checked using Google Earth imagery based upon researcher field experience to delineate wetland land cover classes for six land cover types; papyrus, reed, open water, grazing, cultivated and forest. Sample points were randomly selected using a weighted stratified approach based on six land cover classes (Fig. 1). The basic survey (field survey without soil surveying) took approximately 20 min to complete, with up to an additional hour required for completing the soil survey assessment and sampling. In drained soil sampling sites, infiltration measurements were taken lasting between 35 and 120 min. The time between surveys varied considerably due to large travel times when moving through even short sections of papyrus vegetation. Due to the danger of sampling deep water, open water land cover was not sampled. Surveys were recorded on an android smart phone running Open Data Kit (ODK V1.7.0, Open Data Kit Core Development Team, 2014). A standardised note sheet was filled out for site, vegetation, soil and hydrology qualitative descriptions (see Annex B), and descriptions were made for 193 soil layers. Vegetation and soil samples were analysed at the Uganda National Agricultural Research Laboratories, Kwanda. Fresh and dry weight measurements were taken for 98 soil samples, and analysed for C (n = 77), and pH (n = 60). Due to limited resources nutrient analysis of Ca, K, Mg, P and N was only done for a subset of samples taken from cultivated land cover (n = 43). All data is contained within a single database (Appendix A) and results below describe the mean and standard error for wetland properties by land cover class.

3.1. Site characteristics

The majority of sample sites were located in cultivated and papyrus land covers as these dominate the Kashambya wetland complex. In keeping with the landscape form of Kabale district where wetlands are largely found on the flat valley bottom of steep hillslopes, most sites were classified as channelled or un-channelled valley bottom wetlands (64% and 32% respectively), but two sites were identified as isolated seepage. Intact, papyrus sites were identified as managed by government, compared to cultivated and forest land covers that were perceived as privately managed. Reed and grassland form the transition between intact and degraded land covers, and subsequently management, with two thirds identified as managed by government and a third under private ownership. Communal and cooperative management was low. Results show that a diversity of human activities and influences were found across all land covers. The influence of human disturbance, including burning and harvesting, on natural vegetation shows that 40% of papyrus plots and 27% of reed plots had evidence of burning and 7% of papyrus plots and 38% of reed plots had evidence of biomass harvesting and removal. Anthropogenic impacts were estimated to effect 15% and 26% of biomass in papyrus and reed plots respectively.

3.2. Vegetation assessment

Cultivated land cover was found to have low to medium coverage of a range of plant types; crops, grasses, reeds and weeds. Forest land cover was dominated by trees with moderate to medium coverage with grasses and weeds, and papyrus land cover was dominated by papyrus with little diversity of other plants types. By contrast, reed plots had a large diversity of grasses, reeds and weeds. In over 90% of reed and papyrus land cover classes, soil was protected by vegetation canopy and surface water, while bare soil exposure was low to moderate in forested land cover. In cultivated land cover, a third of plots had high coverage of exposed bare soil. The mean above ground biomass C stock was highest in forest plots; this was highly variable due to differences in plantation age (Table 2). Reed plots contained the highest mean herbaceous above ground biomass C stock, although similar to papyrus vegetation; this has also been found in other studies in Uganda (Saunders et al., 2007, 2014; Jones et al., 2016). Reed plots contained approximately twice the biomass of crop and grassland land covers.

3.3. Water assessment

Seven percent of plots were found to be dry with no water table located. Dry plots were only found under cultivated and forest land covers; likely due to the long-term impacts of eucalyptus plantations, drainage and wetland boundary effects. Fluvial water sources were

[2] Based upon a purchasing power parity factor of 1146. World Bank Purchasing Power Parity factor for Uganda 2016. https://data.worldbank.org/indicator/PA.NUS.PPP?locations=UG.

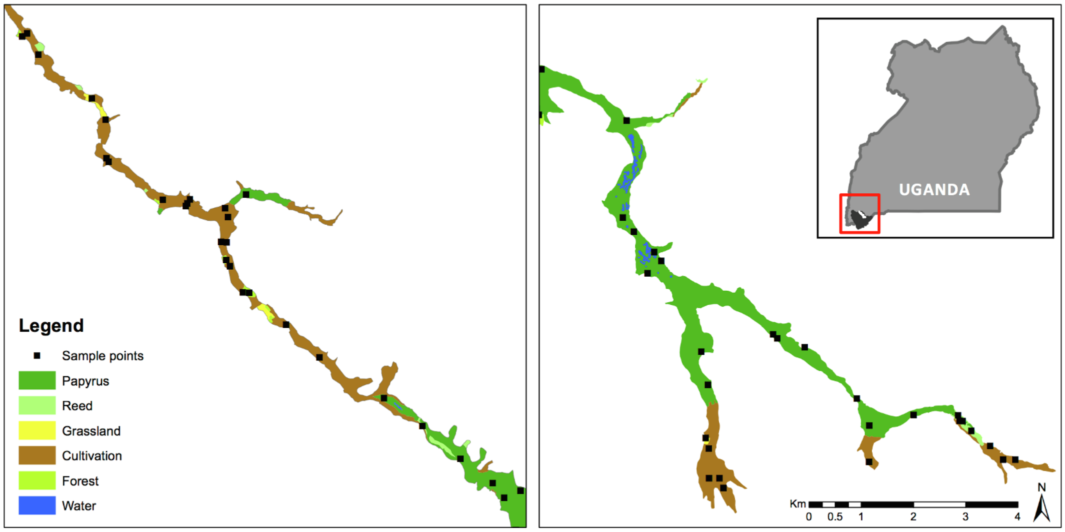

Fig. 1. Map of Kashambya wetland complex. (Left) Lower wetland complex to the north is largely cultivated and drained, and (Right) upper wetland in the south is largely papyrus. Land cover class mapping was based upon manual and semi-manual classification of remote sensing data. Note that water land cover class was to dangerous to sample.

Table 2
Mean above ground biomass estimates by land use class based field measurements on cultivated, forested, papyrus and reed vegetation, and regional appropriate default literature values.

	Above ground biomass carbon (t ha^{-1})	
	Mean	Standard Error
Cultivation	6.6	0.5
Forest	150	80
Grassland	7	2
Papyrus	12	0.5
Reed	15	2

Table 3
Mean water table depth estimates by land use class based on field measurements, Negative values represent water table depth is below the soil surface, NA = not applicable.

	Water Table Depth (cm)	
	Mean	Standard Error
Cultivated	−50	5
Forest	−34	NA
Grassland	−30	10
Papyrus	120	20
Reed	0	10

found in 46% of plots, with 80% of papyrus plots having fluvial water sources. Most of the wetland was classified as temporarily wet (39%), while a third (34%) was classed as permanently wet although the distribution of water regimes changed significantly under land use cover; 84% of cultivated plots were classified as temporarily wet, while in natural land covers, papyrus and reed, were mostly classified as permanently wet (80% and 76% respectively). Grasslands had the largest variation of hydrological regime, with most assessed as seasonally wet (43%). Water table depth was highly heterogeneous across wetland land covers (Table 3); the water table depths in the cultivated and grassland land covers were below the soil surface, and only at one forest plot could the water table depth be measured. In reed land cover, the water table was found above and below the soil surface, and under papyrus, water table was on average over 1 m above the soil surface.

Coverage surface water was found to be high in two thirds of papyrus plots (67%) and largely absent in non-papyrus land cover. Field observations showed that drainage was wide spread across the wetland in all cultivated, forest, and most grassland land covers. The mean drainage depth was greatest in forest sites (80 ± 20 cm) and lowest in cultivated sites (47 ± 3 cm), with most cultivated and forest land covers classified as having high drainage density. Drainage was present in 38% and 13% of reed and papyrus sites respectively, although in the very low density class. The hydrological conductivity of plots was generally high, with 71% of plots classified as having high to moderate hydrological conductivity. Very low hydrological conductivity due to protective barriers or natural slopes was identified in only 28% of cultivated plots, while 40% were found to be prevented from flooding by only distance to central water flows, and 16% were assessed as highly likely to flood. Most papyrus and reed sites were assessed as highly likely to flood, 93% and 88% respectively. Evidence of flooding was low across all sites. Most papyrus and reed plots were assessed as providing medium to high resistance to surface flood water flows due to vegetation structure, while cultivated plots were found to provide low resistance (64%). Water quality observations by land use showed that 15% of near surface water in cultivated sites was classed as good quality (water is still transparent and not discoloured), compared to 86% in papyrus plots and 25% in reed sites. The mean and standard error infiltration rate of drained wetland soils measured was 26 ± 5 cm hr^{-1}, with greatest infiltration rates recorded in cultivated land cover (30 ± 6 cm hr^{-1}).

3.4. Soil assessment

Observations show that 95% of sample plots contained peat. Peat profiles were largely hemic (49%) and fibric (39%) with a smaller amount of sapric peats (12%). Hemic dominated soils were predominantly found in cultivated, forested and grassland wetlands (71%, 67% and 67% respectively), while papyrus plots were mostly fibric (92%) and the reed plots were a mix of fibric and hemic dominated peat soils (63% and 38% respectively). Cultivated and forest land covers were all located on drained peat soils (Fig. 2). Grassland land cover was located on increasingly drier soils, with most located on drained peat soils. Reed sites had the largest diversity of soil types but predominantly located on saturated peats. Papyrus was located on the wettest and weakest formed soils; lake-deposit peats and saturated peats.

Soils classified as drained peats had the greatest bulk density, with seasonally wet, lake-deposit peats and saturated peats had comparable

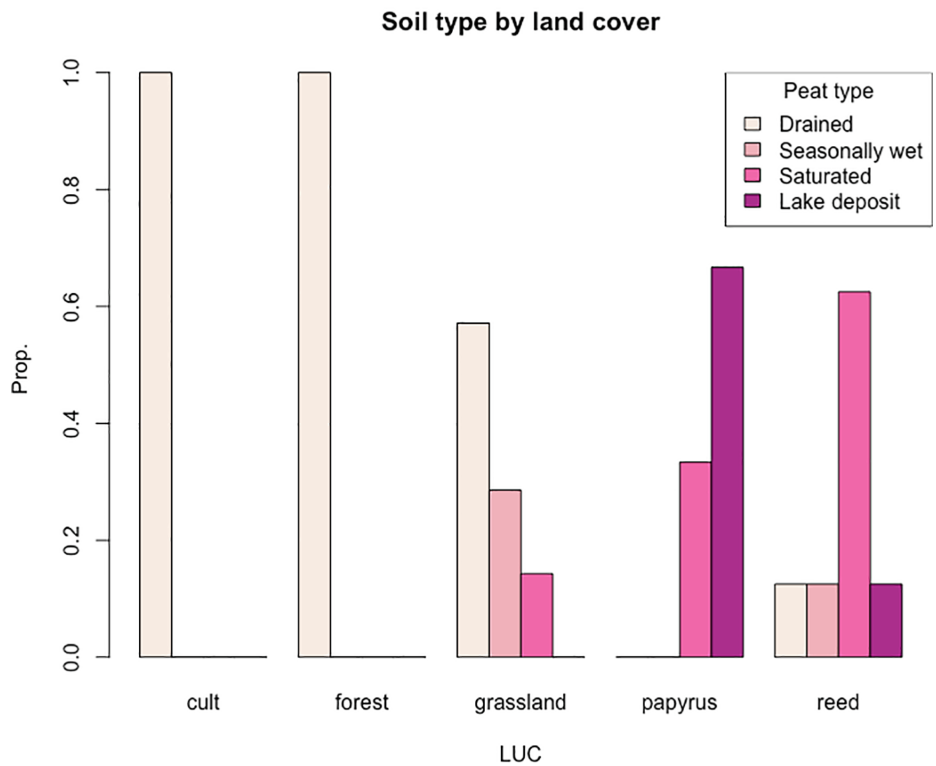

Fig. 2. Proportion of wetland soil types by land use cover class.

Table 4
Mean bulk density, soil organic matter content and percentage carbon soil properties for wetland soil classification.

Peat type	Bulk density ($g\ cm^{-3}$)		Soil organic matter (%)		Carbon (%)	
	Mean	Standard error	Mean	Standard error	Mean	Standard error
Drained	0.38	0.03	38	2	20	1
Seasonal wet	0.22	0.07	38	7	20	4
Permanently wet	0.18	0.06	49	8	26	5
Lake deposit	0.20	0.06	32	8	17	4

Table 5
Mean peat depth and soil C estimates for upper 2 m of wetland soil by land use classification. Note that in a number of papyrus sample plots peat depth exceeded 9 m.

	Peat depth (cm)		Soil C ($t\ ha^{-1}$)	
	Mean	Standard error	Mean	Standard error
Cultivated	210	20	900	100
Forest	5	5	200	120
Grassland	150	51	870	91
Papyrus	340	41	310	30
Reed	480	63	510	140

bulk densities. Comparing bulk density across depths showed drained peats to exhibit a small decline in bulk density with depth, while seasonal peats were the opposite, and permanently wet peat and lake deposit peat bulk densities' were uniform with depth. This might be due to increased presence of mineral soil deposits in the surface and near surface layers due to runoff from neighbouring hill-slopes onto drained peats, and compaction of soils in seasonally wet peats. The percentage of soil organic matter (SOM) and C in all soil types was high (Table 4), with saturated peats having the highest percent of SOM (49 ± 9%) and C (27 ± 5). Organic matter contents were found to be comparable in the seasonally wet and drained peats (38 ± 7% and 38 ± 2%), while lake deposits peats had lower levels of SOM and C (32 ± 8% and 17 ± 4%).

The full peat profile depth was sampled in 81% of plots, with the rest mainly located in papyrus and too deep to fully sample (> 9 m, Table 5). Data shows that 68% of plots contained over 2 m of peat. The mean peat depth across all sites was 300 (± 20) cm while forest contained the shallowest peats soils and reed the deepest. However unknown soil depths in papyrus land covers may skew these results. Carbon stocks in the top 2 m of wetland soils were highly heterogeneous, ranging from 63 to 1748 $t\ ha^{-1}$. Seasonally wet organic soils had the largest soil C stocks (average of 860 ± 90 $t\ ha^{-1}$), followed by drained peat soils (830 ± 110 $t\ ha^{-1}$) with lake deposit peat (290 ± 52 $t\ ha^{-1}$) and saturated peats (280 ± 70 $t\ ha^{-1}$) having similar C stocks. This was largely due to the higher bulk density found in drained and seasonal wet peats. Cultivated land cover had the largest soil C stock and forest the lowest.

Across all sites, pH was very low; lowest in forest sites with pH 3.8 (± 0.6), reed sites with pH 3.9 (± 0.4) and cultivated sites with pH 4.8 (± 0.1). Nutrient analysis was only carried out in cultivated and forested land uses (n = 24), resulting in no data for non-drained soils. The mean C:N ratio of all samples was 22 ± 1. Mean calcium (Ca) levels were 3900 ± 600 ppm, potassium (K) 62 ± 4 ppm, magnesium (Mg) 1100 ± 100 ppm and phosphorous (P) 12 ± 1 ppm. These soils were found to contain higher levels of Ca, an excess of Mg, moderate amounts of K and deficient levels of P based upon national soil nutrient status classifications (Fig. 3) (NARO, 2015).

Surface deposition evidence was observed in 16% of soil profiles, mostly in saturated peats soils where half showed evidence of surface soil deposition. Evidence of fluvial deposition was found in approximately a quarter of all plots, with increasing frequency in saturated peats where three quarters of plots showed evidence of fluvial

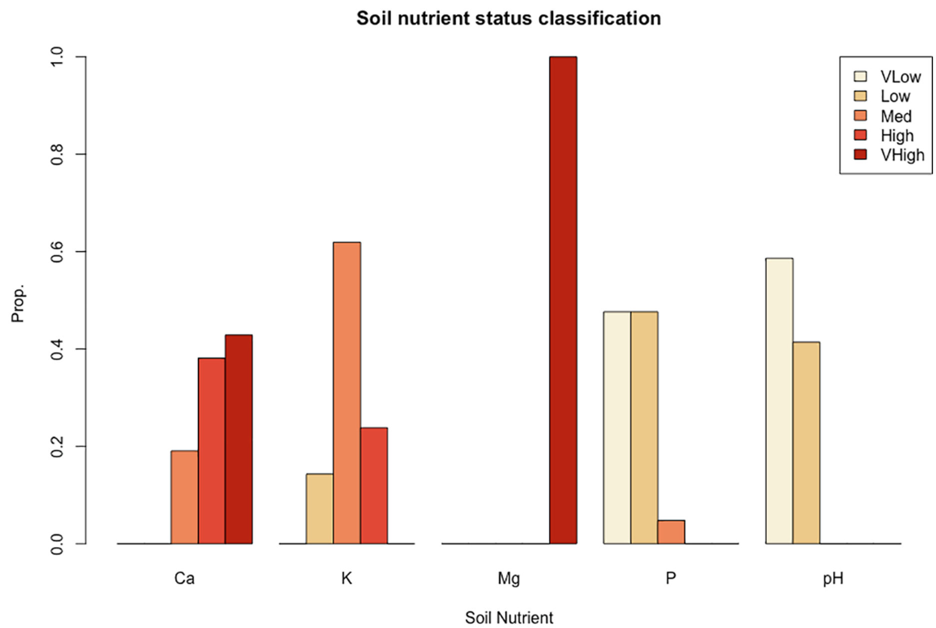

Fig. 3. Soil nutrient classification status of wetland soils in cultivated and forested land cover as a proportion of sampled soils (n = 24). Nutrient status classification is based upon National Agricultural Research Organisation (Uganda) guidelines of soil nutrients.

deposition. Evidence of soil erosion was generally low and found in approximately a quarter of plots. Evidence of soil erosion was observed in 45% of drained peat soil and 25% of saturated peats.

3.5. Wetland ecosystem service accounting

3.5.1. Water provisioning services

Papyrus had the greatest availability of water followed by reed and grassland, while cultivated and forest sites had no water availability (Table 6 and Fig. 4). Daily climate data was downloaded from near Kabale town, approximately 30 km from the wetland (−1.258395°, 29.952513°). Mean annual reference evapotranspiration (Et_o) was calculated to be 950 ± 10 mm and mean annual precipitation was 900 ± 150 mm. Grasslands had the largest rainfall excess, i.e. annual rainfall was greater than evaporation, while forest and papyrus had low rainfall excess. Reed, cultivated and water were estimated to have a rainfall deficit where evaporation exceeded rainfall.

3.5.2. Water regulating services

Water quality in reed and papyrus plots was assessed as good in 100% and 62% of sites respectively. By contrast, water samples in approximately two-thirds of cultivated sites were classified as poor. Due to a lack of surface water for sampling, there was a small sample size in reed, forest and grassland land covers. All forest plots and

Table 6
Summary of estimated ecosystem services provision by land cover classes based on fieldwork and accounting tool assessment. Positive water balance values represent a rainfall surplus and positive carbon flux values represent a net sequestration of carbon. * Represents values and assumptions derived from literature. NB that all water land cover estimates are based on assumptions due to fieldwork dangers. Std. Err. = standard error.

		Cultivation		Forest		Grassland		Papyrus		Reed		Water*
		Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.	Mean
Available water	($m^{-3}\,ha^{-1}$)	0	0	0	0	200	200	12,000	2400	1700	800	20,000
Water balance	($m^{-3}\,ha^{-1}\,y^{-1}$)	−2000	1500	1000	1500	1800	1500	700	3000	−2500	1500	−1000
Water quality classification	Poor	0.58		NA		1		0.15		0		0
	Fair	0.33		NA		0		0.23		0		0
	Good	0.08		NA		0		0.62		1		1
Water purification classification	Negative	0.36		0		0		0		0		0
	Weak negative	0.48		1		0.14		0		0		0
	Weak positive	0.16		0		0.71		0.27		0.75		0
	Positive	0		0		0.14		0.73		0.25		1
Flood storage classification	None	0.16		0.25		0.17		0		0		0
	Low	0.68		0.75		0.83		0.14		0.43		0
	Moderate	0.16		0		0		0.14		0.29		0
	High	0		0		0		0.71		0.29		1
Total ecosystem carbon	($t\,ha^{-1}$)	890	64	330	210	780	160	320	20	530	82	0
Carbon flux	($t\,ha^{-1}\,y^{-1}$)	−10	7	−13	10	0	6	13	3	−0.7	3	0
Net primary production	($t\,ha^{-1}\,y^{-1}$)	3.9	0.1	16	0.4	5.0	0.4	16	2	5.0	0.4	0
Soil organic matter oxidisation	($t\,ha^{-1}\,y^{-1}$)	14	7	30	20	5	8	0.3	1	0.6	2	0
Vegetation removals	($t\,ha^{-1}\,y^{-1}$)	0	0	0	0	0	0	0.9	0.4	2.	1	0
Food production	(US$ $ha^{-1}\,y^{-1}$)	3000	250	0	0	140	52	0	0	30	20	0
Potato yield	($t\,ha^{-1}\,y^{-1}$)	14.3	0.9	0	0	0	0	0	0	0	0	0
Milk yield	($dm^{-3}\,ha^{-1}\,y^{-1}$)	0	0	0	0	410*	150	0	0	*80	52	0

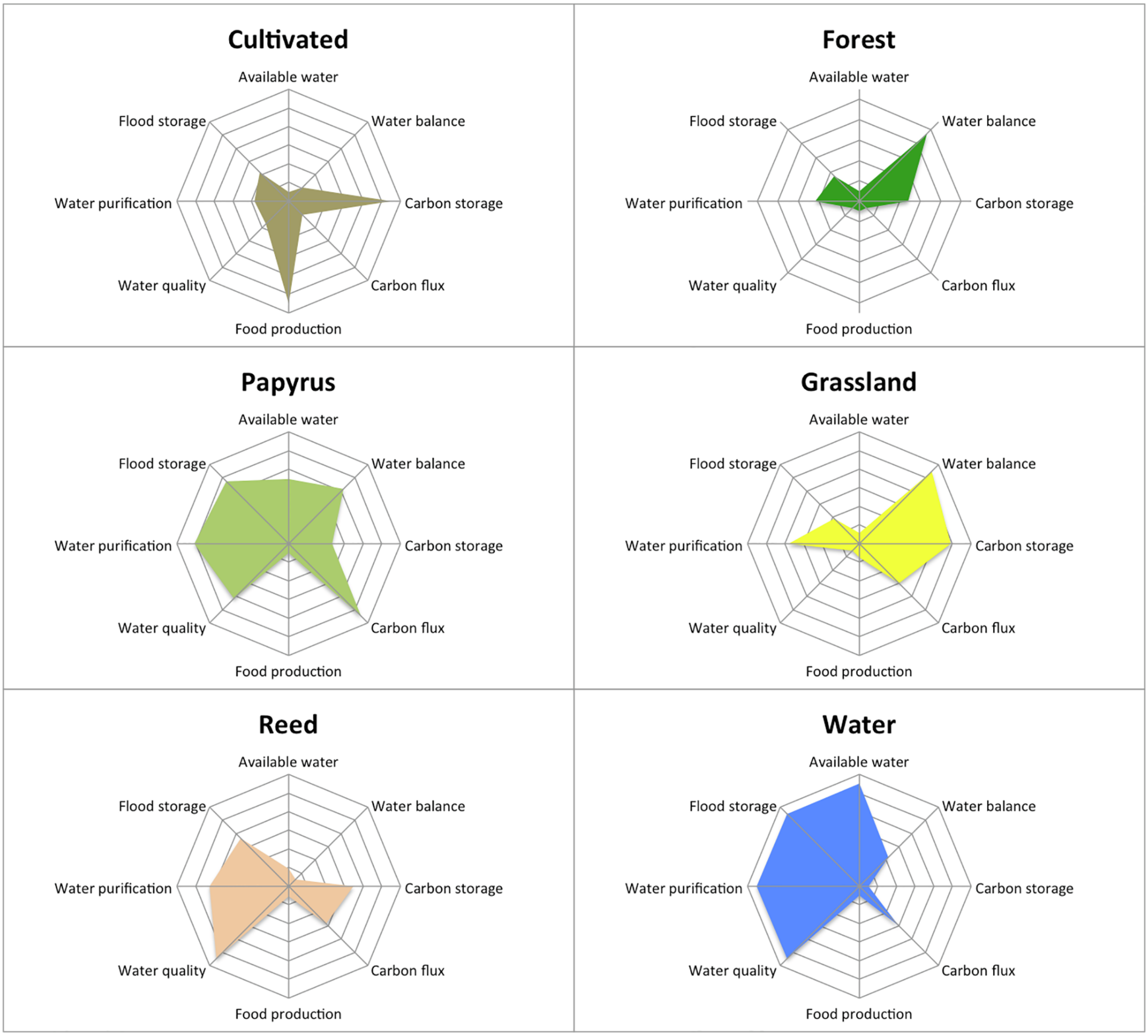

Fig. 4. Radar diagrams displaying the provision of ecosystem service (ES) by wetland land cover. Service provision values have been centred and rescaled so that outside edge of diagram represents the highest provision of an ES by any land cover class and centre represents the lowest ES provision of any land cover.

approximately 85% of cultivated plots were assessed to have a negative contribution to water quality. All papyrus and reed plots were assessed as likely to purify water, with approximately three quarters of papyrus and a quarter of reed plots providing a strong positive contribution to water quality. The majority of cultivated, forest and grassland plots were assessed as having no or low contribution to flood water storage. Papyrus plots were most likely to provide high floodwater storage. Approximately a third of reed plots provided high floodwater storage.

3.5.3. *Climate regulating services*

Analysis shows that ecosystem C stocks were largely determined by soils type and that degraded land cover generally contained higher C stocks with cultivated land cover storing the largest total amount of C in both vegetation and the top 2 m of soil (890 ± 64 t ha^{-1}). Papyrus stored the lowest amount of ecosystem C (320 ± 20 t ha^{-1}). Negligible aquatic above ground biomass and peat soil in the upper 2 m of the water column was assumed for open water land cover. Forest and papyrus were estimated to have the largest rates of NPP and C sequestration (16 ± 0.4 and 16 ± 2 t ha^{-1} y^{-1} respectively), and cultivation had the lowest rates of NPP (3.9 ± 0.1 t ha^{-1} y^{-1}). Carbon emissions due to organic soil oxidation are estimated to be largest in forest and cultivated land covers (30 ± 20 and 14 ± 7 t ha^{-1} y^{-1} respectively). Papyrus and reed land cover had the lowest rates of C emissions (0.3 ± 1 and 0.6 ± 2 t ha^{-1} y^{-1} respectively). Analysis suggests that 1.0% of papyrus and 10.0% of reed biomass is affected by biomass removal, equal to 0.9 ± 0.4 and 2 ± 1 t ha^{-1} respectively. Papyrus was the only land cover assessed to be a net sink of C, with a mean sequestration rate of 13 ± 3 t ha^{-1} y^{-1}. Reed and grasslands were approximately C neutral (−0.7 ± 3, 0 ± 6 t ha^{-1} y^{-1} respectively), while cultivated and plantation forest on wetlands were estimated to be large net sources of C emissions (10 ± 7 and 13 ± 10 t ha^{-1} y^{-1} respectively).

3.5.4. *Food production*

The income from potato cultivation was estimated to be US$ 3000 ± 1000 ha^{-1} y^{-1}, while milk production on grassland and reed

Table 7
Estimated provision of ecosystem services by Kashambya wetland complex, Kabale. * Negative flux values represent a net loss of water from wetlands and positive carbon fluxes represent net sequestration.

	Total ecosystem service provision	Standard error
Available water (m^3)	7,000,000	1,300,000
Water balance ($m^3\ y^{-1}$)*	−40,000	180,000
Total carbon storage (t)	500,000	40,000
Carbon flux ($t\ y^{-1}$)*	3000	4000
Food production (US$ yr^{-1})	1,000,000	83,000

Level of ecosystem service provision		Percentage of wetland coverage
Water quality	Good	41
	Fair	26
	Poor	32
Water purification contribution	Positive	43
	Weak positive	24
	Weak negative	19
	Negative	14
Flood storage capacity	High	42
	Med	15
	Low	37
	None	6

was valued as US$ 140 ± 52 and 30 ± 20 $ha^{-1}\ y^{-1}$ respectively as a result of the seasonal inundation of reed land cover.

3.5.5. *Assessment of ecosystem services in Kashambya wetland*

By scaling ES provision by areal extent of land cover, an assessment was made of the total ES provision for the full wetland complex (Table 7). Results show that Kashambya wetland provides large storage of water, although it is a net source of water vapour. Within the wetland's vegetation and upper 2 m of soil, we estimate that the wetland stores approximately 500,000 ± 40,000 t of C and sequesters 3000 ± 4000 t of C annually. The value of food production was estimated to be US$ 1,000,000 ± 83,000. We estimated that water quality was most likely to be classed as *good*, with only one third likely to be classed as poor due to high visible sediment loading. Approximately 40% of the wetland was likely to contribute positively to water quality due to the conditions of vegetation and soil to purify water. Approximately one third of the wetland was classified as having a negative contribution to water quality. The proportion of the wetland providing *high* and *low* levels of floodwater storage was approximately balanced.

4. Discussion and conclusions

Data on tropical wetland properties are limited, which restricts the understanding of the ES they provide and constrains modelling efforts for understanding important ecosystem dynamics. The approach presented here provides a quick and simple field methodology for identifying important wetland ecosystem properties by combining quantitative and qualitative data collection in a structured sampling strategy. Due to wet conditions and deep water where it was difficult to take soil profiles and samples in weakly formed soils, the assessment may underestimate the soil conditions and ES provided by papyrus wetlands, in particular, peat depths and soil C stocks. This could be improved by increasing the soil sampling depth, but would have implications on time and budgets. Results show high heterogeneity in wetland properties and ES provision, particularly between different land covers and peat soil types, and exemplify the anthropogenic impact on ecosystem properties, functions and ES. The use of land cover class average values of ES provision can be crude, as wetland characteristics and properties are highly variable and subsequently levels of ES provision within the same land use classes are likely to have a large range. Aggregation by land use partially accounts for the large uncertainty in estimates and fails to capture important spatial processes, such as variation in peat depths across the wetland, or location such as upstream-downstream dynamics on water quality. The aggregation of wetland properties by land cover introduces uncertainty, which could be reduced by more sophisticated Geographical Information System (GIS) analysis to reflect the role of soil type, hydrological position and water regime. The geo-located survey results could be combined with remote-sensing databases to provide detailed mapping of wetland properties and ES to improve estimates.

Another key source of uncertainty is likely due to the temporal variations in wetland properties and functions as shown by high uncertainty in estimates of ES connected to carbon and water fluxes, such as water table depths, soil moisture, vegetation coverage and climate; these are likely to have a large impact on wetland functions of SOM decomposition, NPP and evapotranspiration. Temporal variation in properties and functions is likely to produce significant impacts on ES provision on an inter-seasonal and inter-annual basis; this simple modelling approach is limited with respect to understanding water dynamics; e.g. water quality assessment are very crude, and water quality is likely very dependent upon the timing of rainfall. Dynamic simulation modelling approaches could improve understanding of system dynamics, particularly temporal variations in ecological functions under changes in environmental conditions. However there is a paucity of longitudinal data through which to build a greater understanding of water flows, and water quality. This tool provides a good baseline measure to allow future changes to be quantified.

The importance and interaction of anthropogenic influences on wetland structure and properties are readily evident; papyrus was mainly found on weakly formed peat soils under lake type conditions, often in close proximity to main fluvial flows making peat soils very difficult to drain; this is likely to explain why these areas remain intact. Conversely, cultivation largely occurs on more structured and decomposed peat soils in areas easier to drain and till. Eucalyptus forestry stands were mainly mature and located on wetland edges; this is linked to their historical use in lowering water table tables and making wetland margins suitable for cultivation. Reed and grassland land covers occur in the transition between papyrus and cultivated areas, and show large variability in soil type, ecosystem properties and ES. As discussed above, the assessment tool does not account for differences within individual land classes, which also includes changes in management practises, such as the use of fertilizers within cultivated areas. This limits the detail available to support land managers to understand future changes to ES use with climate or land management decisions. More sophisticated modelling of wetland ES is required to inform wetland land management decision-making in respect to supporting

decisions for wetland management techniques. This tool provides valuable data to support further modelling efforts but we recognise the limitation of this modelling approach. Investment into the development of simple methodologies for collecting temporal data should be made, using the same ethos as that underlies this tool; simple and cheap. Methods for capturing seasonal and annual variation in wetland properties could draw upon citizen science approaches for recording data on water depths or annual crop yields at appropriate time intervals, or simple, digital devices for automatically sensing water table depths. Alternatively, some aspects of this survey tool could be reapplied at different times of the year, to capture those variables, such as water quality or fibre production, which would be expected to have temporal variability.

We present a field survey and accounting methodology to assess ES provision from tropical wetlands in East Africa, and apply this to the Kashambya wetland complex in Kabale district in south western Uganda. Results show that anthropogenic activities have had a major influence on wetland properties and subsequently ES provided by the wetland with approximately 40% of the wetland having undergone change to potato cultivation, in addition to other anthropogenic impacts. Our assessment shows that the Kashambya wetland is a large stock of water and releases water vapour into the surrounding landscape. The wetland is also a large stock of C and is currently a net sink of atmospheric C, sequestering over 3000 t of C annually. The wetland also provides a high amount of water quality and flood storage regulating services. While this assessment of ES is limited in how it captures the role of spatial interactions and seasonality of ES, it provides a useful methodology for rapidly reporting an initial wetland ES assessment, and the data collected provides a strong basis to support improved wetland ES modelling and assessments.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.04.019.

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